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AERONAUTICAL RESEARCH LABORATORY

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Aircraft Structures Technical Memorandum 492

CRKGRW - CRACK GROWTH PROGRAM USER'S MANUAL (U)

by

J. Paul and D. Lombardo

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SUMMARY

This document describes the theory and input requirements to the CRKGRW Fortran computer program, which is used to calculate crack growth rates using data on material properties, load sequences and crack geometry.

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NOTATION

a	– crack length or depth (see Figs 4, 5 and 6)
a_0	– initial crack length or depth
B	– constant in modified Forman equation
b	– width or half width of specimen (see Figs 4, 5 and 6)
C	– constant in crack growth equation
C_P	– Wheeler retardation factor
c	– crack depth or length (see Figs 4, 5 and 6)
c_0	– initial crack depth or length
da/dN	– constant amplitude crack growth rate
dc/dN	– constant amplitude crack growth rate
K	– stress intensity
K_c	– fracture toughness
K_{TH}	– threshold stress intensity
ΔK	– change in stress intensity
L	– characteristic length
M	– constant in crack growth equation
m	– Wheeler's shaping exponent
n	– exponent in crack growth equation
P	– constant in modified Forman equation
Q	– constant in modified Forman equation
R	– stress ratio ie $\sigma_{min}/\sigma_{max}$
R_y	– extent of current yield zone
r	– hole radius
t	– thickness or half thickness of specimen (see Figs 4, 5 and 6)
β	– geometrical factor
σ	– current stress level
σ_{alt}	– cycle alternating stress
σ_{max}	– cycle maximum stress
σ_{mean}	– cycle mean stress
σ_{min}	– cycle minimum stress
σ_{red}	– reduction in stress for Willenborg model
σ_y	– yield stress
$\Delta\sigma$	– cyclic stress range

DEFINITIONS

The terms LAYER, MISSION, FLIGHT, SEGMENT and BLOCK are used in this manual. Their definitions, *as they apply in this manual*, are set out below (also refer to Fig. 8).

LAYER – A layer consists of one or more constant amplitude loading cycles.

MISSION – A mission is a group of layers defined in a specified manner.

FLIGHT – A flight is one application of a mission.

SEGMENT – A segment consists of one or more flights of the same mission applied consecutively. The flights within a segment are numbered from one upwards.

BLOCK – A block consists of all the segments specified in the data file.

Note: Random sequences can be handled by CRKGRW if each cycle is considered as a separate layer.

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1. INTRODUCTION

This report is a manual for using CRKGRW Version 2.0 (hereafter called CRKGRW) to calculate crack growth using various models. Relevant background theory is also included.

CRKGRW is essentially an upgrading of the FORTRAN 77 program CRKGRW Version 1.0 with program bugs removed and more options added. CRKGRW Version 1.0 is itself a modification of CRACKS IV. This was a FORTRAN IV program written by R. M. Engle Jr of the Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base.

This manual also includes elements from two ARL reports on CRACKS IV [Refs 11 and 12].

2. CRACK GROWTH MODELLING

The essence of crack growth programs is to calculate the change in crack length resulting from the application of a single load cycle. This is repeated for each load cycle in the sequence resulting in the total crack length and the time to failure being calculated.

The basic material data used for the calculations are generally available in the form of a da/dN versus ΔK relationship (see Section 3.2). In order to calculate the increment of crack growth per load cycle, the value of the change in the stress intensity factor ΔK at the crack tip must be determined. This factor requires a knowledge of the crack length, specimen and crack geometry, and the magnitude of the load cycle so that a β factor can be calculated. For linear-elastic fracture mechanics the equation relating ΔK with the above factors is given in Equation 1a.

$$\Delta K = \Delta\sigma\sqrt{\pi a}\,\beta \qquad (1a)$$

This equation does not take into account the subsequent effect of large stress cycles which may retard the growth rate. This can be incorporated in a number of ways (as described in Section 3.3).

CRKGRW calculates crack growth layer-by-layer according to the equation below.

$$a_i = a_{i-1} + (da/dN)_i * (\text{Number of cycles in the layer}) \qquad (1b)$$

where $(da/dN)_i$ is crack growth rate for a single cycle in the layer.

If failure occurs within the layer, then CRKGRW will re-calculate the crack growth in the layer cycle-by-cycle. In this case only, the crack length is updated after each cycle until failure occurs.

3. THEORETICAL BACKGROUND TO PROGRAM

3.1 Introduction

This section has been included so that the user of the CRKGRW program will have some theoretical knowledge as to how the program calculates various parameters. Crack length a and depth c for each solution will be defined in Section 3.4.

3.2 Material Data

The material data required by CRKGRW are:

i) material yield stress,
ii) fracture toughness,
iii) stress intensity threshold, and
iv) da/dN versus ΔK.

The first three are simply numbers but the fourth can take many forms. CRKGRW allows several different da/dN versus ΔK relationships and these are described in the next section.

3.2.1 da/dN versus ΔK

Five equations are presented which attempt to model the behaviour of the da/dN versus ΔK curve (Fig. 1) by taking various parameters into account.

a) Paris equation [Ref. 1]

This equation has the following form:-

$$da/dN = C(\Delta K)^n \tag{2}$$

The program requires the specification of the parameters C and n.

b) Forman equation [Ref. 2]

The Forman equation has the following form:-

$$\frac{da}{dN} = \frac{C(\Delta K)^n}{(1-R)K_c - \Delta K} \tag{3}$$

This equation takes into account the influence of the of the stress ratio R and the material fracture toughness K_c.

c) Forman equation modified [Ref. 3]

The modified Forman equation has the following form:-

$$\frac{da}{dN} = \frac{C(\Delta K - (PR+Q))\Delta K^n}{(1-BR)K_c - \Delta K} \tag{4}$$

This equation has been demonstrated to reproduce Fig. 1, for different stress ratios, very accurately. The 5 parameters required are C, n, P, Q and B.

d) Walker equation [Ref. 4]

Walker's equation in original form was an extension of the Paris equation to include the influence of the stress ratio R. CRKGRW uses the following form:-

$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{(1-M)}}\right]^n \tag{5}$$

The three parameters C, M and n are required by CRKGRW.

e) Tabulated data

Often the most convenient form of input of constant amplitude data for da/dN versus ΔK is tabulated values. These are obtained from graphs such as Fig. 1.

3.2.2 Evaluation of Material Constants

Representative material data having been selected, (either from handbooks or from constant amplitude test results), they now need to be fitted to the equations presented in section 3.2.1. The Paris and Forman constants C and n are sometimes quoted in materials data books. This section looks at the determination of the modified Forman equation constants as an example.

i) Evaluation of P and Q. P and Q describe the threshold stress intensity factor range and its movement with R. Figure 2(a) shows how the constants can be obtained from the da/dN data, if more than two stress ratios are given.

ii) Evaluation of B. B describes the variation of the fracture toughness with R. Figure 2(b) shows how B can be evaluated from the da/dN data.

iii) Evaluation of C and n. C and n are obtained from the line of best fit passing through the approximately linear centre section. C is calculated from the vertical intercept and n from the slope. Some compromise may be necessary when evaluating C and n to obtain the best fit over the full range of R.

3.3 Retardation Models

Retardation models take into account the reduction in crack growth rate after the application of a high load. At present the CRKGRW program contains two working retardation models. These models are:-

a) Wheeler [Ref. 5]

This model introduces a retardation factor C_P which reduces the growth rate function, f, as described by the relationship

$$a_n = a_0 + \sum_{i=1}^{n} C_{P_i} f(\Delta K_i) \tag{6}$$

where

$C_{P_i} = \left(\frac{R_y}{a_P - a}\right)^m \quad for \quad (a + R_y < a_P)$

or

$C_{P_i} = 1 \quad for \quad (a + R_y \geq a_P)$ ie: no retardation

and

$a_P - a =$ the distance from the current crack tip to the furthest point of the elastic-plastic interface.

The parameter m must be determined experimentally or obtained from data handbooks. The parameter is also a useful tool in calibrating the program run to test data.

b) Willenborg [Ref. 6]

Willenborg modelled retardation by reducing both the maximum and minimum stress of cycles following an overload. The reduction in these stresses is given by:-

$$\sigma_{red} = \frac{\sigma_y}{\beta}\sqrt{\frac{2\,(a_P - a)}{a}} - \sigma_{max} \tag{7}$$

provided that σ_{max} has been preceded by a higher load, σ_1 which produced a_P

This retardation model has the effect of:

i) reducing the stress ratio R leaving ΔK unchanged; or

ii) reducing ΔK for $R = 0$; or

iii) making ΔK and R both equal zero when $\sigma_1/\sigma_{max} \geq 2.0$

In its standard form this model requires no additional input parameters.

3.4 Stress Intensity Solutions

Every crack growth program is required to calculate the stress intensity solution. CRKGRW has the capability to handle several different solutions for β . These solutions are described below.

Note: In the solutions below, if no definition of a and/or c is given then:
i) the problem is regarded as one-dimensional and
ii) a is defined as along the surface of the specimen.

a) Surface Flaw Solution

The surface flaw solution written into CRKGRW is the Newman and Raju solution [Ref. 7, Equation 17]. Figure 4 shows the definition of a and c. The equation for β is given below:-

$$\beta = \left[M_1 + M_2\left(\frac{c}{t}\right)^2 + M_3\left(\frac{c}{t}\right)^4\right] g f_\phi f_w \tag{8}$$

provided the following conditions are satisfied

$0 < c/a < 2 \qquad a/b < 0.5, \qquad 0 < \phi < \pi$

where $\phi = 0$ for a and $\phi = \frac{\pi}{2}$ for c.

When the crack becomes a through-crack β is automatically made unity since the problem is now a through-crack in a plate.

Definition of the variables can be found in Ref. 7, pages 12-13.

Note: - This solution includes its own finite width correction factor.
- a in this manual is the same as c in Ref. 7 and c in this manual is the same as a in Ref. 7.

b) Constant value of β

BETA option 1 allows the user to input a constant value of β into the program.

c) Finite width correction

BETA option 2 allows for a finite width correction. The correction used was developed by Fedderson [Ref. 8]. The equation is shown below:

$$\beta = \sqrt{\frac{1}{\cos\left(\pi\left(\frac{a+r}{b}\right)\right)}} \tag{9}$$

where b is the half width of the plate and r is the radius of the hole, if any, in the plate .

This correction may be used with any of the other solutions except for the Surface Flaw solution and BETA options 10 and 11.

d) Tabular input of β solution

BETA options 3 and 4 allow tables of β versus a/L to be entered.

e) Bowie solution for a single crack

BETA option 5 is the Bowie solution for a single crack from a circular hole [Ref. 14, Table 1]. The equation is shown below:-

$$\beta = 0.6762 + \frac{0.8734}{\left(0.3246 + \frac{a}{r}\right)} \tag{10}$$

f) Bowie solution for a double crack

BETA option 6 is the Bowie solution for a double crack from a circular hole [Ref. 14, Table 1]. The equation is shown below:-

$$\beta = 0.9439 + \frac{0.6865}{\left(0.2772 + \frac{a}{r}\right)} \tag{11}$$

g) ASTM compact tension specimen

BETA option 7 allows the solution for ASTM compact tension specimens [Ref. 10, Equation 12]. This equation is shown below (see also Fig 7). Note that the spectrum is input as loads and not stresses.

$$\beta = \frac{f\left(\frac{a}{b}\right)}{t\sqrt{\pi a b}}$$

where

$$f\left(\frac{a}{b}\right) = 4.55 - 40.32\left(\frac{a}{b}\right) + 414.7\left(\frac{a}{b}\right)^2 - 1698\left(\frac{a}{b}\right)^3 + 3781\left(\frac{a}{b}\right)^4 - 4287\left(\frac{a}{b}\right)^5 + 2017\left(\frac{a}{b}\right)^6$$

for $0.2 \leq a/W \leq 0.8$

h) Grumman compact tension specimen

BETA option 8 allows the Grumman compact tension specimen to be modelled [Ref 13, Equation 40]. See Fig. 7 for the geometry of the specimen. The equation for β is:

$$\beta = \frac{(0.1229 + 16.4098(\frac{a}{b}) - 37.395(\frac{a}{b})^2 + 54.7667(\frac{a}{b})^3)}{\sqrt{\pi a}/t}$$

for $a/b \leq 0.5$

and

$$\beta = \frac{(114.054 - 830.132(\frac{a}{b}) + 2327.177(\frac{a}{b})^2 - 2890.811(\frac{a}{b})^3 + 1382.206(\frac{a}{b})^4)}{\sqrt{\pi a}/t}$$

for $a/b > 0.5$

i) Liu crack from a circular hole

BETA option 9 allows the Liu solution for a double quarter crack from a circular hole. The equation used is shown below:-

$$\beta = 1.12 * \frac{2}{\pi}\left(0.6762 + \frac{0.8734}{\left(0.3246 + \frac{a}{r\sqrt{2}}\right)}\right) \tag{12}$$

Note the correspondence between this solution and the Bowie solution for a single crack.

j) Corner crack from a hole

BETA option 10 allows the Newman and Raju solution for a corner crack from a hole [Ref. 7]. Figure 5 shows the definition of a and c. The equation for β is given below:-

$$\beta = \left[M_1 + M_2\left(\frac{c}{t}\right)^2 + M_3\left(\frac{c}{t}\right)^4\right] g_1 g_2 g_3 f_\phi f_W \qquad (13)$$

provided the following conditions are satisfied

$0.2 \leq c/a \leq 2 \quad 0.5 \leq c/t \leq 1, \quad (r+a)/b < 0.5, \quad 0 < \phi < \frac{\pi}{2}$

where $\phi = 0$ for a and $\phi = \frac{\pi}{2}$ for c.

Definition of the variables can be found in Ref. 7, pages 20-22.
See also the note for the Surface flaw solution.

k) Surface crack in a hole

BETA option 11 allows the Newman and Raju solution for a single or double embedded crack in a hole [Ref. 7]. Figure 6 shows the definition of a and c. The equation for β is given below:-

$$\beta = \left[M_1 + M_2\left(\frac{c}{t}\right)^2 + M_3\left(\frac{c}{t}\right)^4\right] g_1 g_2 g_3 f_\phi f_W \qquad (14)$$

provided that the same conditions given for BETA option 10 are satisfied.

Definition of the variables can be found in Ref. 7, pages 16-20.
See also the note for the Surface flaw solution.

4. DATA INPUT TO CRKGRW

The input data file contains a number of headings, called KEYWORDS, followed by the relevant information on the next line or lines for that keyword. This section describes some areas where care must be taken to produce an error free data file and then a description of all the possible data inputs follows.

UNITS

Any consistent set of units may be used.

COMMENT CARDS

A C at the beginning of a line represents a comment card. Care must be taken not to place comment cards where data is expected by the program. Comment cards are only allowed before a keyword or after all information associated with the current keyword has been input.

DEFAULT VALUES

For some of the options discussed in the following section, if a zero is specified then a default value will be used (which may be non-zero).

KEYWORDS

CAPITALS should always be used in the data file for the keywords. The program will not recognise lower case. Lower case may be used when writing a comment or heading line only.

All keywords should be placed at the beginning of the line (ie: they must begin in column 1).

ORDER OF KEYWORDS

Some keywords may be placed anywhere in the data file while others must occur in a certain order. To avoid problems, use the order which is specified in section 4.1 .

OPTIONAL KEYWORDS

Not all of the keywords need to appear in the data file. Those keywords that are optional are indicated in section 4.1 as they are discussed.

NUMERICAL INPUT

All the numerical values required by the keywords may be entered in free format. That is, the values may appear anywhere on the line in the order that they are required with either a comma or a space separating them.

ERRORS IN INPUT

The program has been designed to recognize some of the errors that may occur in the input file. However, it will not catch silly errors such as negative dimensions. Some of the more common errors are given in section 4.3.

4.1 KEYWORDS

The keywords recognised by CRKGRW as flagging a data segment are:

LINES PER PAGE
TITLE
EQUATION
MATERIAL
THRESHOLD
LIMITS
ANALYSIS
LOADS
SPECTRUM
PRINT
PLOT
END DATA

4.1.1 LINES PER PAGE segment (optional)

This segment defines the number of lines of output that will be printed per page. The default is 80.

Line 1: LINES PER PAGE
Line 2: L

L = the number of lines per page (must be an integer ≥ 40)

4.1.2 TITLE segment (optional but should be used)

Line 1: TITLE
Line 2: n where n is the number of lines in the title.
Line 3: 1^{st} line of title information.
Line 4: 2^{nd} line of title information.
...
Line n+2: n^{th} line of title information.

The title text will be printed at the head of the output file. A maximum of 80 characters is allowed per line.

4.1.3 EQUATION segment

This segment determines the way the da/dN versus ΔK data will be input to the program. There are eight different equations the program will accept. They are:-

PARIS
PARIS-BI (bi-linear version of the Paris equation)
FORMAN
FORMANMOD
WALKER
WALKER-BI (bi-slope version of the Walker equation)
DA/DN
R-DA/DN

CRKGRW allows two definitions of stress intensity, K :-

i) $K = \sigma\sqrt{\pi a}\,\beta$

and

ii) $K = \sigma\sqrt{a}\,\beta$ (NASA convention)

CRKGRW will default to the first definition unless the keyword NASA is placed after the above equation options.

Line 1: EQUATION
Line 2: Characters 1 to 10 – one of the above equation keywords.
Characters 11 to 14 – NASA (if required).

4.1.4 MATERIAL segment

The nature of input in this segment is determined by the option previously chosen in the EQUATION segment.

Line 1: MATERIAL
Line 2: This is a comment line, which is used to describe the material in use (maximum of 80 characters).
It is written to the output file.
Line 3: This line provides the data for the EQUATION chosen.

a) PARIS option
Line 3: C and n

b) PARIS-BI option
Line 3: C_1 , n_1 , ΔK_{TRANS} , C_2 , n_2

This gives a bi-linear Paris fit with the parameters
C_1 and n_1 for $\Delta K < \Delta K_{TRANS}$
and C_2 and n_2 for $\Delta K > \Delta K_{TRANS}$.

c) FORMAN option
Line 3: C, n, K_c

d) FORMANMOD option
Line 3: C, n, K_c, P, Q, B

e) WALKER option

Line 3: C, M, n

f) WALKER-BI option

Line 3: C_1, M_1, n_1
Line 4: C_2, M_2, n_2
Line 5: $(da/dN)_{TRANS}$, ΔK_{TRANS}

Figure 3(a) shows the set of lines generated by the standard Walker equation for a range of R values. Note that there are no lines for $R < 0$ as, at present, CRKGRW considers all negative loads to be zero. Figure 3(b) shows the effect of the WALKER-BI option. As can be seen this splits the Walker equation into two regions such that:

C_1, M_1, and n_1 apply in region 1
and C_2, M_2, and n_2 apply in region 2
where the transition between the two regions is defined by:
$da/dN = (da/dN)_{TRANS}$ and $\Delta K = \Delta K_{TRANS}$ on the $R = 0$ line.

g) DA/DN option

A table of values of ΔK versus da/dN

Line 3: n - the number of points in the table (must be an integer)
Line 4: 1st point, ΔK_1, $(da/dN)_1$
Line 5: 2nd point, ΔK_2, $(da/dN)_2$
...
Line n+3: nth point, ΔK_n, $(da/dN)_n$

If line 3 is negative then CRKGRW assumes that lines 4 to n+3 are in a separate data file. The name of this data file will be requested by CRKGRW when it is needed.

h) R-DA/DN option

Sets of constant amplitude crack propagation data for up to ten values of stress ratio R may be entered. The data for each value of R must be placed in separate files. File names will be requested at runtime and must be given in order of increasing R. The format of each file is as follows:-

Line 1: R value
Line 2: n - the number of points in the table (must be an integer)
Line 3: 1st point, ΔK_1, $(da/dN)_1$
Line 4: 2nd point, ΔK_2, $(da/dN)_2$
...
Line n+2: nth point, ΔK_n, $(da/dN)_n$

The final line of the MATERIAL segment requires the parameters K_Q and σ_y.

K_Q - maximum permissible value of stress intensity.
σ_y - material yield stress.

4.1.5 THRESHOLD segment

Line 1: THRESHOLD

Line 2: ΔK_{TH}, R_{MULT}

ΔK_{TH} - is the threshold value of ΔK.

R_{MULT} - parameter if crack growth is R-dependent
Default = 0

Crack increments will be calculated if

$$K > \Delta K_{TH}(1 - R_{MULT} * R)$$

4.1.6 LIMITS segment

Line 1: LIMITS

Line 2: a_0 , a_{max} , N_0 , R_{CUT}

a_0 - Initial length or half length of crack. Care must be taken with the definition of a_0. Refer to the theory section to determine the definition of a pertaining to the β solution being used.

a_{max} - Maximum length or half length of crack.
Default = 10^{20}

N_0 - Initial cycle number. Cycles applied during the run will be numbered starting with this value.
Default = 1

R_{CUT} - Calculated stress ratios are truncated to this value.
Default = 1.

4.1.7 ANALYSIS segment

Several options are available for analysing the stress intensity for various specimen geometries. Two or more of these options may be selected to operate simultaneously and different options can operate over different crack lengths.

Line 1: **ANALYSIS**

An option is selected by choosing one of the keywords below, followed on the next line by the various numerical parameters. Valid keywords are:-

SURFACE
RETARD
BETA
END

One or more of the keywords SURFACE, RETARD and BETA must be used.

a) **SURFACE** option

Line 1: SURFACE
Line 2: C1 , C2 , C3 , C4

C1 - initial crack depth, c.
Default = a_0.
C2 - thickness of plate, t.
C3 - width of plate, $2b$.
C4 - maximum crack depth, c_{max}
Default = thickness of plate.

Note - This analysis does not require a BETA solution option.
- This analysis is three dimensional, with a along the surface and c through the depth.

b) **RETARD** option

Line 1: RETARD
Line 2: C1 , C2 , C3 , C4 , C5 , C6

C1 - defines the retardation model to be used:
C1 = 1; Wheeler retardation model
C1 = 2; Willenborg retardation model

C2 - indicates to the program whether plane stress or plane strain is to be assumed.
C2 = 0: plane stress
C2 = 1: plane strain
Default = plane stress

C3 - If C1=1 then C3 is Wheeler's retardation parameter m.
- If C1=2 then C3 (if not zero), represents the maximum overload in the Gallagher-modified Willenborg model.

C4 - flags whether a re-run of the program, without retardation, is to occur.
C4 = 0: job re-run without retardation

C4 = 1: no re-run.
Default = job re-run

C5 - gives any initial overload condition of the specimen at program start.
Default = 0.0

C6 - gives the initial plastic zone size of the specimen at program start due to a previous overload, a_P .
Default = 0.0

Note: if C1=2 and C3 $\neq$ 0 then only the FORMAN and FORMANMOD equations may be used.

c) **BETA** option

In the BETA options, the upper and lower crack size limits define the range over which a particular β solution will be applied. Thus it is possible to have several β solutions being used over different phases of the crack's growth.

Note: if some of the values (C1, C2, ... C6) required below are zero, then they must be entered as such. Leaving blanks is not acceptable and will cause the program to crash.

Line 1: BETA
Line 2: C1, C2, C3, C4, C5, C6

C1 = 1: Constant correction factor model.
- C2 - correction factor
- C3 - lower crack limit
  Default = initial crack size
- C4 - upper crack limit
  Default = infinity
- C5 - zero
- C6 - zero

C1 = 2: finite width correction model
- C2 - effective plate half width
- C3 - lower crack limit
  Default = initial crack size
- C4 - upper crack limit
  Default = infinity
- C5 - zero
- C6 - zero

C1 = 3: Tabulated function of a/L versus β
- C2 - half width of specimen
- C3 - n - number of points in table
- C4 - lower crack limit
  Default = initial crack size
- C5 - upper crack limit
  Default = infinity

C6 - zero

plus Line 3: Table heading (80 characters maximum)
Line 4: 1^{st} point, $(a/L)_1$, β_1
Line 5: 2^{nd} point, $(a/L)_2$, β_2
...
Line n+3: n^{th} point, $(a/L)_n$, β_n

L is a characteristic length which for CRKGRW is the half width of the specimen.
Hence, the a/L versus β table is actually $a/(\frac{1}{2}$ width) versus β

C1 = 4: Exactly the same as C1=3. The reason for the inclusion of two table options is that the two tables can be applied over different stages of the crack's growth. This is achieved by specifying different upper and lower crack limits (C4 and C5).

C1 = 5: Uniaxial Bowie solution for single crack from a circular hole.
C2 - radius of hole, r.
C3 - lower crack limit
Default = initial crack size
C4 - upper crack limit
Default = infinity
C5 - zero
C6 - zero

C1 = 6: Uniaxial Bowie solution for two cracks from a circular hole.
C2 - radius of hole, r.
C3 - lower crack limit
Default = initial crack size
C4 - upper crack limit
Default = infinity
C5 - zero
C6 - zero

C1 = 7: ASTM Compact Tension specimen
C2 - width of specimen, b.
C3 - thickness, t.
C4 - lower crack limit
Default = initial crack size
C5 - upper crack limit
Default = infinity
C6 - zero

C1 = 8: Grumman Compact Tension specimen
C2 - width of specimen, b.
C3 - thickness, t.
C4 - lower crack limit
Default = initial crack size
C5 - upper crack limit

Default = infinity

C6 - zero

C1 = 9: Lui solution for a double quarter crack from a circular hole.

C2 - radius of hole, r.

C3 - initial crack size, a_0.

C4 - final crack size

C5 - zero

C6 - zero

C1 = 10: Newman and Raju solution for a corner crack extending from a hole. Three dimensional.

C2 - radius of hole, r.

C3 - single or double crack

C3 = 1: single crack

C3 = 2: double crack

C4 - initial crack depth, c_0.

Default = thickness of specimen, t.

C5 - half width of specimen, b.

C6 - thickness of specimen, t.

C1 = 11: Newman and Raju solution for a surface crack extending from inside circular hole.

C2 - radius of hole, r.

C3 - single or double crack

C3 = 1: single crack

C3 = 2: double crack

C4 - initial crack depth, c_0.

Default = half thickness of specimen, t.

C5 - half width of specimen, b.

C6 - half thickness of specimen, t.

d) **END**

Line 1: END

This keyword is required to terminate an ANALYSIS segment. It must always appear in the data file after all the analysis options have been completed.

4.1.8 LOADS segment

This segment defines the load sequences for one or more missions. Each mission is defined as a sequence of loads (or stresses) and the number of applications of each load. The order in which the various missions are specified is not important (the order in which they will be applied is controlled by the SPECTRUM segment). The program numbers them consecutively as they appear in this segment.

Line 1: LOADS
Line 2: TITLE
Line 3: NBLKS , LPRT
Line 4: MULT

TITLE – comment line describing load sequence (80 characters maximum).
NBLKS – maximum number of times the whole program block is to be repeated (must be an integer).
LPRT – print mission specifications to output file.(must be an integer)
LPRT = 0: print information
LPRT = 1: do not print information
MULT – multiplication factor on all loads read in.

Note: This option is very useful as it allows non-dimensional spectra or strain gauge spectra to be used and converted to stresses or loads with the MULT factor.

There are three ways of entering the loads into the program. Each mission starts with a keyword/header line. The keywords are:-

MAX-MIN
R-DELTA
MEAN-ALT

The keywords are in columns 1–10, followed by an optional 20 character heading describing the mission in columns 11 – 30

Lines of data follow, each representing a single layer of the mission. A layer consists of a pair of stress parameters followed by the number of cycles for which they are to be applied.

Line 5: MAX-MIN
Line 6: 1st data line, σ_{max_1} , σ_{min_1} , No. of cycles
Line 7: 2nd data line, σ_{max_2} , σ_{min_2} , No. of cycles
...
Line n+5: nth data line, σ_{max_n} , σ_{min_n} , No. of cycles
Line n+6: −9999 −9999 −9999

Note: Line n+6 is used as a termination line due to the free format read.

Line 5: R-DELTA
Line 6: 1st data line, $\Delta\sigma_1$, R_1 , No. of cycles
Line 7: 2nd data line, $\Delta\sigma_2$, R_2 , No. of cycles
...

Line n+5: n^{th} data line, $\Delta\sigma_n$, R_n , No. of cycles
Line n+6: −9999 −9999 −9999

where $\sigma_{max} = \Delta\sigma/(1 - R)$
and $\sigma_{min} = \sigma_{max} - \Delta\sigma$

Line 5: MEAN-ALT
Line 6: 1^{st} data line, σ_{mean_1} , σ_{alt_1} , No. of cycles
Line 7: 2^{nd} data line, σ_{mean_2} , σ_{alt_2} , No. of cycles
...
Line n+5: n^{th} data line, σ_{mean_n} , σ_{alt_n} , No. of cycles
Line n+6: −9999 −9999 −9999

where $\sigma_{max} = \sigma_{mean} + \sigma_{alt}$
and $\sigma_{min} = \sigma_{mean} - \sigma_{alt}$

Note: When the BETA options 7 and 8 are chosen in the analysis section, the layers must be presented as loads and NOT stresses.

To terminate the LOADS segment the final line must have the following keyword:-

END LOADS

Note: At present CRKGRW truncates all negative loads to zero.

4.1.9 SPECTRUM segment

This segment defines the pattern in which missions are selected from the data presented in the LOADS segment to make a complete block.

Line 1: SPECTRUM
Line 2: NCYC, HR/BL
Line 3: NSEGS, IPRT
Line 4: $NFLTS_1$, $MISSN_1$
Line 5: $NFLTS_2$, $MISSN_2$
...
Line NSEGS + 3: $NFLTS_{NSEGS}$, $MISSN_{NSEGS}$

NCYC – this is the total number of cycles in a block
HR/BL – this is the total number of hours per block.
NSEGS – the number of segments in the block. That is, the number of lines in the spectrum definition to follow (must be an integer).
IPRT – print mission specifications to output file (must be an integer).
IPRT = 0: print information.
IPRT = 1: do not print information.
NFLTS – number of times a mission is to be repeated (must be an integer).
MISSN – the mission number from LOADS segment (must be an integer).

4.1.10 PRINT segment (optional)

This segment controls the print of information to the output file.

Line 1: PRINT
Line 2: I , J , K , L, Δ

I - crack growth output every I'th block (integer).
J - crack growth output every J'th segment (integer).
K - crack growth output every K'th flight (integer).
L - layer-by-layer crack growth output every L'th flight (integer).
Δ - crack growth output whenever Δa and/or $\Delta c \geq \Delta$.

A zero corresponds to no output and is the default.

4.1.11 PLOT segment (optional)

This segment allows the user to obtain output files containing lists of two variables. The output files will have a '.PG[number]' extension. The format of this segment is shown below:-

Line 1: PLOT
Line 2: x-variable
Line 3: y-variable

The possible keywords for the variable names are listed below:-

KEYWORD		MEANING
A	-	a
C	-	c
CYCLES		
HOURS		
DA/DN	-	da/dN
DC/DN	-	dc/dN
DELKA	-	ΔK in a direction
DELKC	-	ΔK in c direction
BLOCKS		

The '.PG[number]' file will contain two columns of numbers. The first column will be the x-variable and the second column will be the y-variable. These files can then be used in conjunction with inhouse plot routines. The interval of writes to this file is linked to that of the PRINT segment. Care must be taken to ensure that huge files are not created.

4.1.12 END DATA segment

This keyword signals to the program that the input has ended.

4.2 LIMITATIONS

CRKGRW has the following limits:-

- Maximum of 50000 layers per mission.
- Maximum of 50 missions per block.
- Maximum of 200 segments per block.
- Maximum of 100 values in the ΔK , da/dn table (DA/DN option).
- For the R-DA/DN option, the total number of lines in all the files must not exceed 100.
- The name of the data input file must not exceed 24 characters (including the .DAT extension - see section 5).
- The filenames requested by the DA/DN and R-DA/DN options must not exceed 10 characters.

4.3 COMMON INPUT FILE ERRORS

There are a number of errors which may occur when CRKGRW reads the input data file. Two common errors, along with their causes are given below.

Error - CRKGRW error 'Unrecognised keyword'

Causes - Illegal keyword

- Comment line without a 'C' at the beginning
- Using lowercase letters in the keyword
  eg: Surface, Lines Per Page, BeTA
- Mistyped keyword
  eg: PRNIT, WAL KER, LINESPER PAGE
- The keyword does not begin in the leftmost column of the line (column 1)
  eg: C This is a comment line with the 'C' in column 1
  ANALYSIS
  C The previous line will not be recognised because the
  C ANALYSIS keyword does not begin in column 1.

Error - Program crashes while trying to read the data file

Causes - Placing a real number where an integer is expected.
  eg: LPRT must be either 0 or 1, however, putting 0., 0.0, 1. or 1.0 in the input file will cause the program to crash.
- not putting in enough numbers as required by the option
  eg: The BETA option requires 6 numbers to be on the line after BETA, but some of the sub-options require only four or five non-zero values. For example, if C1=2 is chosen then only C2, C3 and C4 are non-zero but C5 and C6 must still be entered as zeros.
- There was no -9999, -9999, 9999 line at the end of a set of layers in the LOADS segment. This will cause the program to attempt to read the next keyword as a number which causes the crash.

5. RUNNING CRKGRW

The input file which contains all the information for CRKGRW must have a .DAT extension to its name (eg: F18LUG.DAT, SPAR.DAT, TEST.DAT). The name may be any legal combination of upper and lower case characters. When CRKGRW is run, it will ask for the name of this file. The name should then be entered *in uppercase only.* You do not need to type the .DAT extension since CRKGRW automatically searches for .DAT files. For example, entering F18LUG will cause CRKGRW to read data from F18LUG.DAT.

CRKGRW produces several output files. If your input file was F18LUG.DAT then the output files produced would be :-

FILE	FILE INFORMATION
F18LUG.EXT	indicates if extrapolation occurs.
F18LUG.OUT	main output file.
F18LUG.PG1	1st plot output file.
F18LUG.PG2	2nd plot output file, etc

The program requires the name of the data file at runtime, which it requests. MATERIAL options DA/DN or R-DA/DN may require separate data files. These should be created before running CRKGRW and their names entered when CRKGRW requests them. To end the entry of MATERIAL data files to CRKGRW, the keyword 'NOMORE' should be typed instead of a filename.

When reading through the data input file, CRKGRW will stop at the first error it encounters. When this happens you must edit the data file to remove the error and then re-run CRKGRW.

An example data file is presented in Appendix 1. This data file is only intended to be an example of a variety of options which were presented in Section 4.

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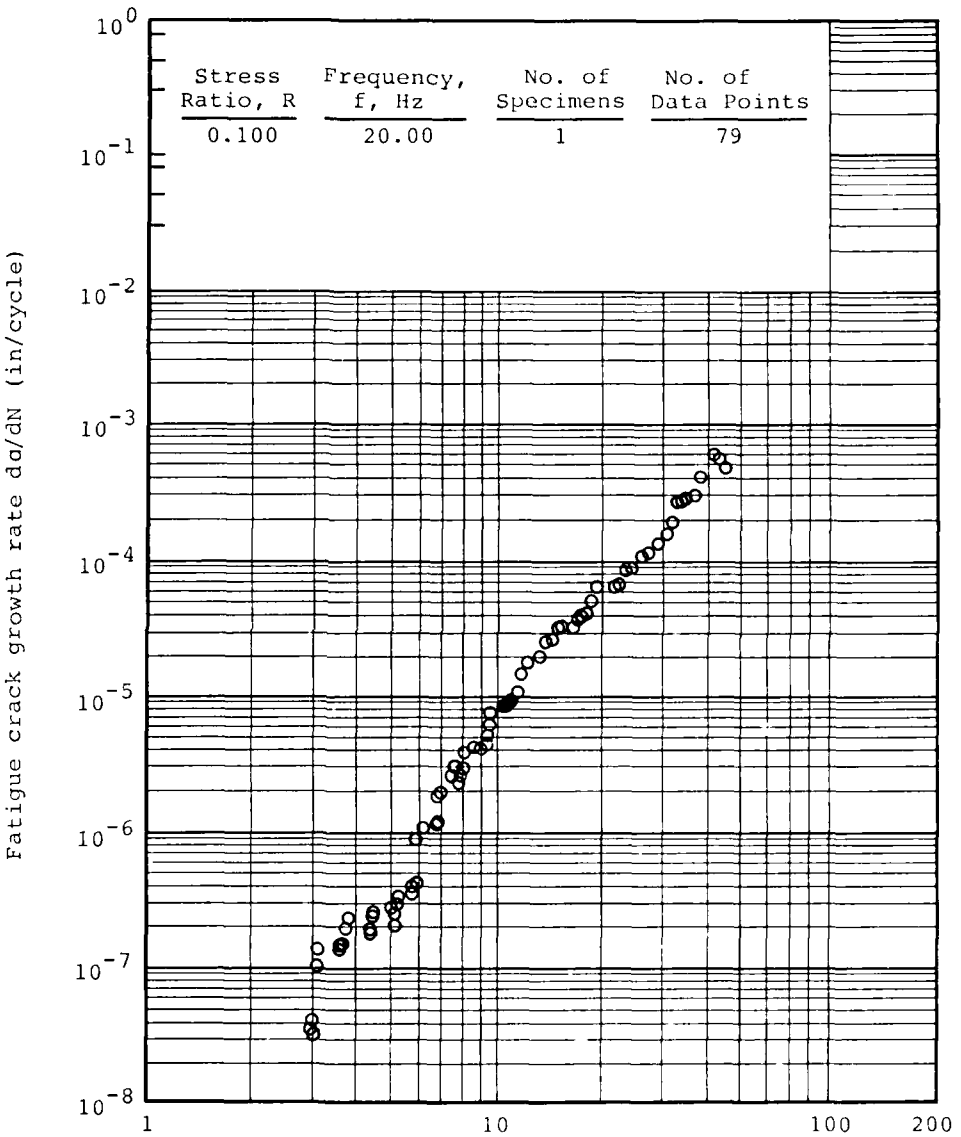
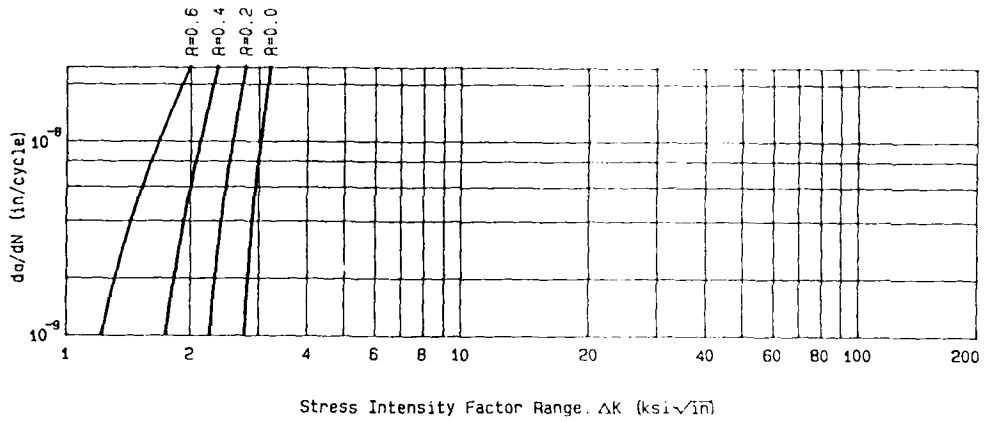


FIGURE 1: EXAMPLE da/dN DATA
CRACK GROWTH DATA FOR ALUMINIUM ALLOY
7050-T736 (REF. 3)



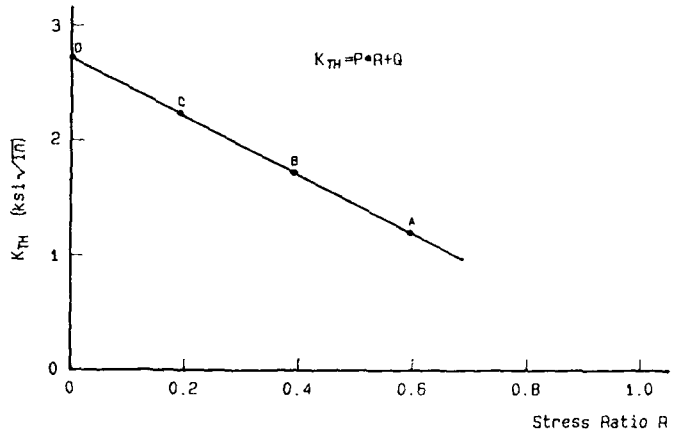
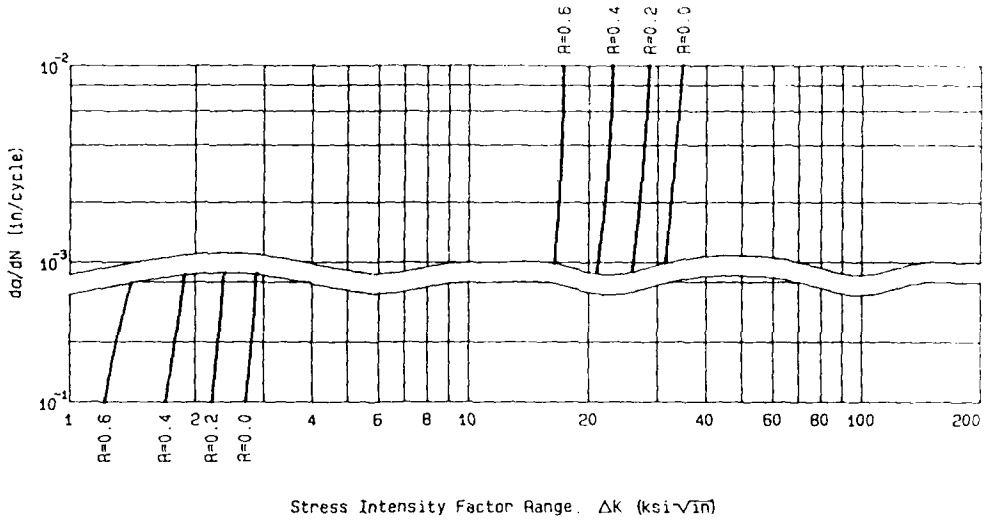


FIGURE 2(a): RELATIONSHIP BETWEEN STRESS INTENSITY THRESHOLD AND STRESS RATIO (REF. 3)



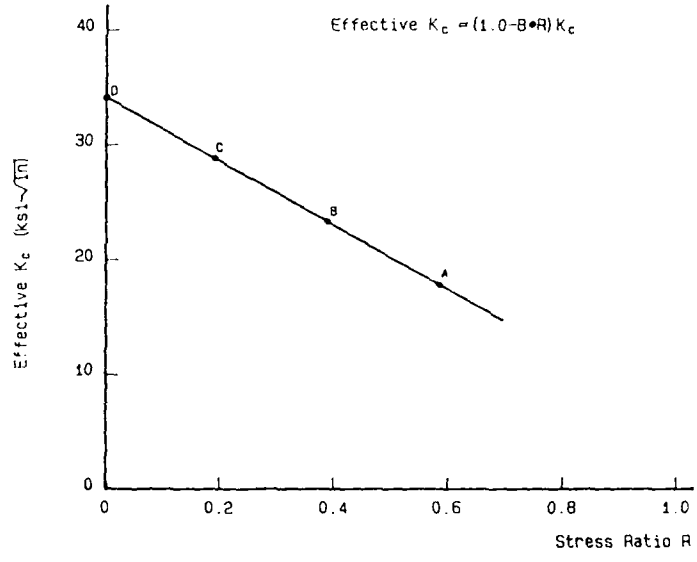


FIGURE 2(b): RELATIONSHIP BETWEEN EFFECTIVE TOUGHNESS AND STRESS RATIO (REF. 3)

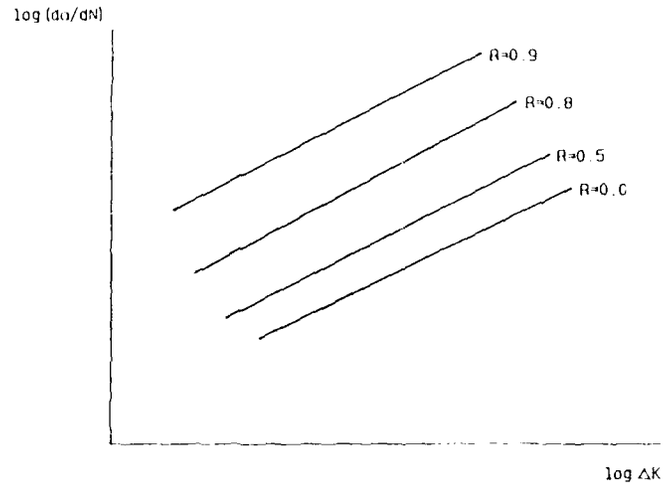


FIGURE 3(a): STANDARD WALKER EQUATION

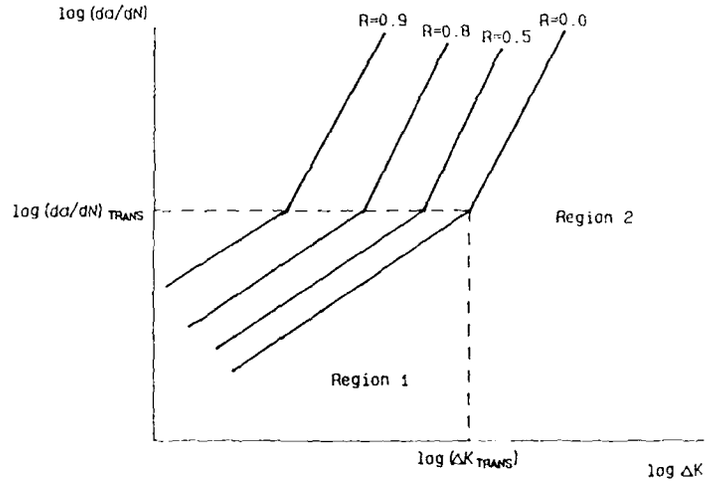


FIGURE 3(b): WALKER BI-LINEAR EQUATION

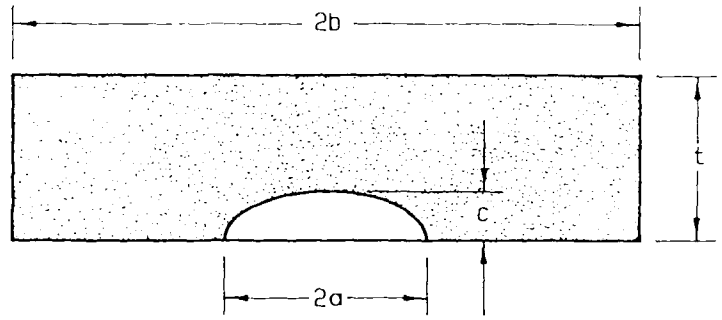


FIGURE 4: DEFINITION OF a AND c FOR A SURFACE FLAW

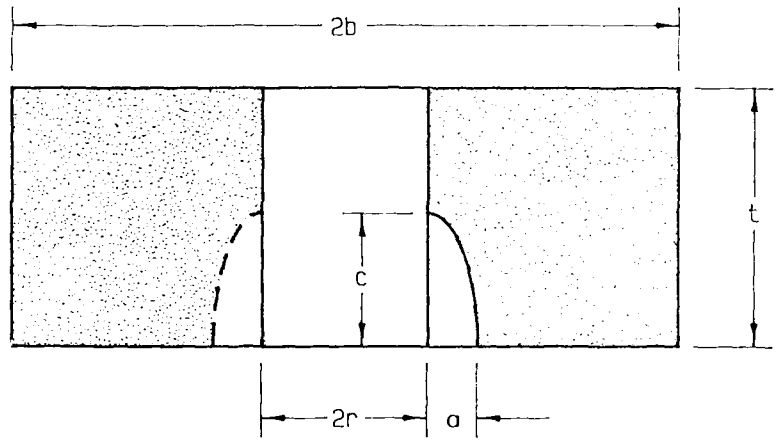


FIGURE 5: DEFINITION OF a AND c FOR A SINGLE OR DOUBLE QUARTER ELLIPTICAL CORNER CRACK FROM A HOLE

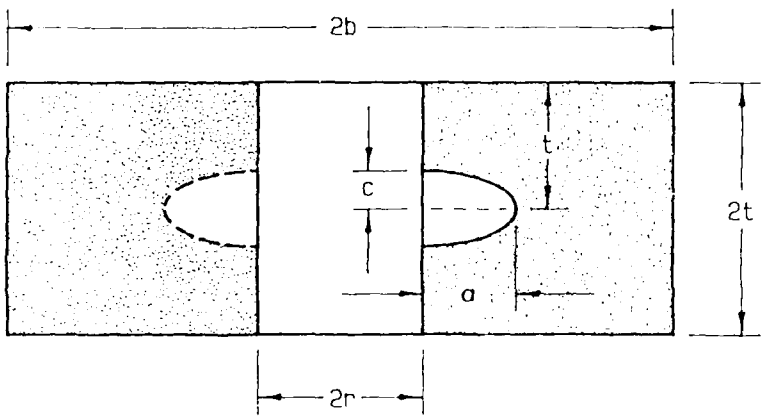
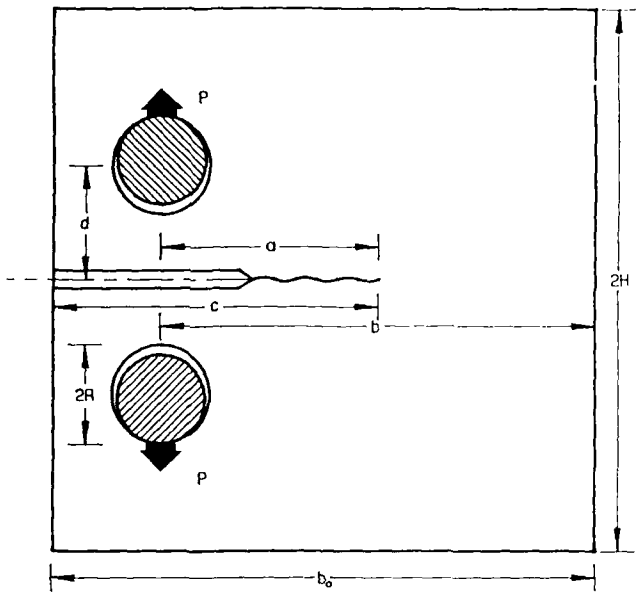
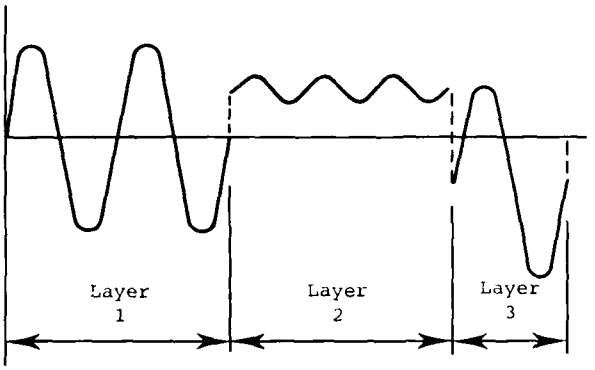


FIGURE 6: DEFINITION OF a AND c FOR A SINGLE OR DOUBLE EMBEDDED CRACK IN A HOLE

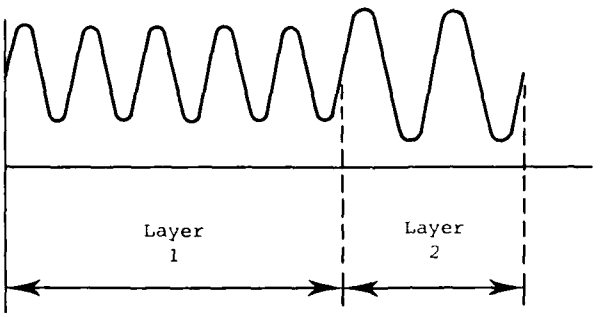


Dimension	ASTM	GRUMMAN
b (in)	2.2, 2.5	2.5
H/b	0.60	0.95
d/b	0.25	0.60

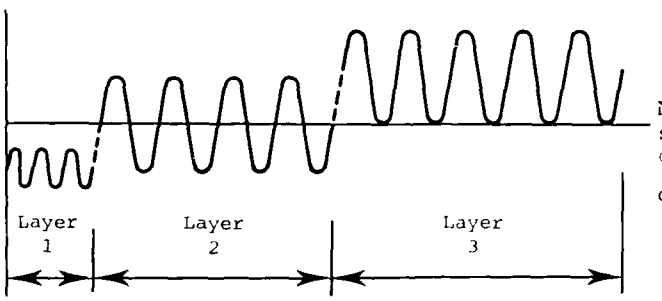
FIGURE 7: ASTM AND GRUMMAN COMPACT TEST SPECIMEN



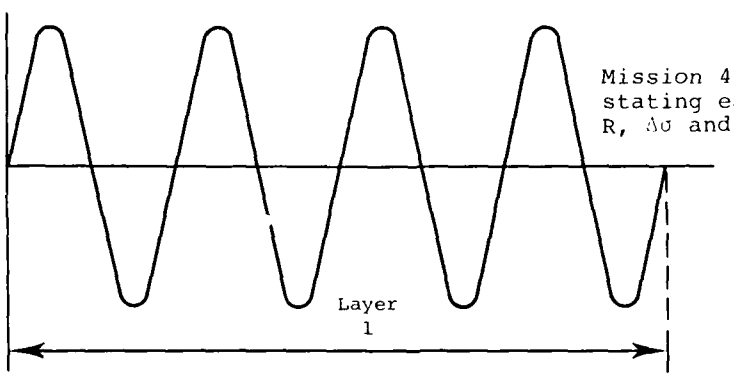
Mission 1 - defined by stating each layer's σ_{max} , σ_{min} and number of cycles



Mission 2 - defined by stating each layer's σ_{mean} , σ_{alt} and number of cycles



Mission 3 - defined by stating each layer's σ_{max} , σ_{mean} and number of cycles



Mission 4 - defined by stating each layer's R, $\Delta\sigma$ and number of cycles

FIGURE 8(a): LAYERS AND MISSIONS

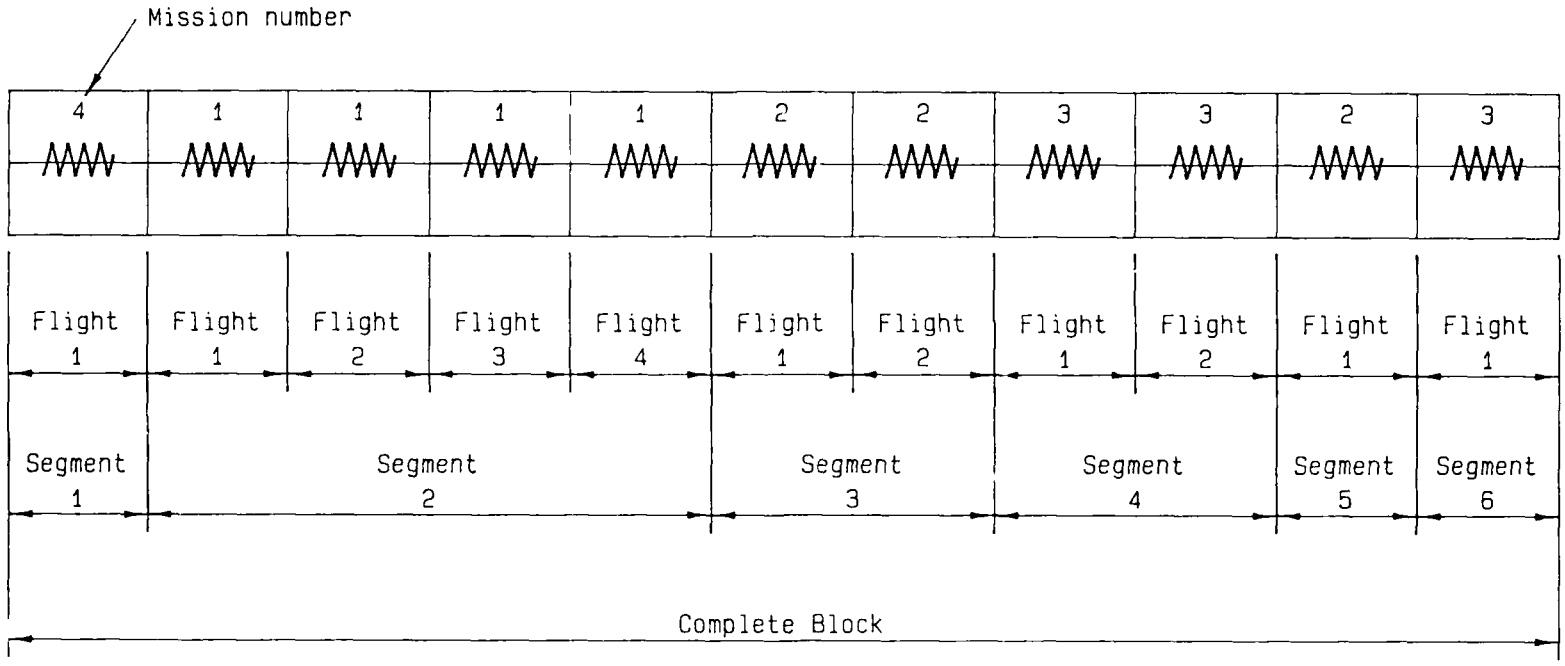


FIGURE 8(b): THE MISSION OF FIGURE 8(a) APPLIED TO FORM A BLOCK

APPENDIX 1

This appendix gives an example CRKGRW data file, with extra options as examples of different inputs.

```
C
C THIS IS A COMMENT LINE EXAMPLE
C
TITLE
4
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
THIS IS A SAMPLE PROGRAM TO DEMONSTRATE THE INPUT
OF INFORMATION INTO CRKGRW.
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
EQUATION
WALKER
MATERIAL
ALUMINIUM ALLOY 7050 - material comment line
1.304E-10, .55, 3.25
50.0    63.0
THRESHOLD
3.0     .1
LIMITS
.01  2.0  0.0  0.0
ANALYSIS
C----- using a two crack Bowie solution
BETA
5    0.25  0.0  0.0  0.0  0.0
C----- with the finite width correction factor
BETA
2    2.0  0.0  0.0  0.0  0.0
END
LOADS
SPECTRUM FULL DATA
100  1
30.0
MAX-MIN
1.0   -0.6    10        )
1.2   -0.7    28        )
0.9   -0.2    19        ) Mission No. 1
0.3    0.0    100       )
0.5    0.3    260       )
-9999  -9999  -9999
MEAN-ALT
1.0    0.2    300       )
0.8    0.1    300       ) Mission No. 2
0.8    0.3    300       )
-9999  -9999  -9999
```

```
END LOADS
SPECTRUM
11853     1000
3    0
7    1          ) Segment 1: 7 flights of mission 1     )
9    2          ) Segment 2: 9 flights of mission 2     ) 1 block
2    1          ) Segment 3: 2 flights of mission 1     )
C------ print every layer
PRINT
0   0   0   1   0
C------- or print every five blocks and whenever crack
C------- growth exceeds 0.05
PRINT
5   0   0   0   0.05
PLOT
A
HOURS
PLOT
DA/DN
HOURS
END DATA
```

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16. ABSTRACT

This document describes the theory and input requirements to the CRKGRW Fortran computer program, which is used to calculate crack growth rates using data on material properties, load sequences and crack geometry.

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